Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Environmental Sciences 10 (2011) 1630 – 1636
Procedia Environmental Sciences

2011 3rd International Conference on Environmental Science and Information Application Technology (ESIAT 2011)

Development and Application of an Integrated Hydrological Model for Lake Watersheds

Qi Zhang

State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, P R China
email: zhanglin994@tom.com

Abstract

Quantitative estimation of surface and subsurface water flow to lakes is important for lake resources management. The calculation of water volume into lakes is also an essential step for estimation of pollutant loads to lakes. This paper presents a mathematical model for coupled simulation of surface and subsurface water flows for lake watersheds, with emphasis on the modelling of several important aspects including groundwater level-soil water storage-surface runoff relation, river-groundwater interactions and lake-watershed hydrological linkage, which are all fundamental for an integrated simulation of hydrological processes for lake watersheds. Field case studies were also given as examples to test the model's suitability and capability. The model is grid-based spatially distributed to facilitate the discretisation of the high heterogeneity of land use types and soil properties. The model can be used as a useful tool to quantify components of hydrological processes for detailed watershed water balance analysis, and to assess impacts of watershed management strategies on the security of lake water resource

Keywords: Surface-subsurface water flow; Integrated simulation; Lake watershed; Poyang lake; WATLAC

1. Introduction

Lakes receive water flows from watershed in terms of surface runoffs (stream flow and overland flow) and subsurface water flow (groundwater flow). These water flows contribute to the water balance of the lake, and hence quantifying these water flow components is very important for the assessment of lake water balance in response to climate change and human activities in the catchment.

Practice has proven that mathematical models indeed provide useful and effective ways to explore the hydrological processes of lake watersheds. For a better understanding, an integrated simulation approach is preferred for lake watersheds in order to take into account the surface-subsurface water flow interaction and the lake-watershed hydrological connection. Quite a number of existing models have been reported

doi:10.1016/j.proenv.2011.09.257

that are capable of simulating both surface and subsurface water flows in a coupled manner, including MODHMS [1], GSFLOW [2], and MIKE SHE [3], to name a few. Depending on the modelling purposes and the specific cases, different types of models and different levels of model complexities may be selected. For lake watersheds, however, certain characteristics must be considered, such as the presence of multiple river catchments within the watershed contributing surface runoffs to the lake and the hydrological connection between the lake and the watershed. In some cases, the groundwater discharge to lakes is also important and must be simulated appropriately. For these purposes, and to overcome some of the limitations in the existing models, a new model WATLAC, was developed [4]. WATLAC is grid-based and is designed to simulate the spatial distribution of soil water storage and surface runoff and subsurface water flow movement driven by rainfall and evaporation. Processes including canopy interception, unsaturated soil water storage, soil water percolation to groundwater, river flooding propagation, saturated groundwater flow, water exchange between groundwater and river are considered. In particular, model design considers the hydrological characteristics of lake watersheds, such as multiple river catchments within the watershed and the variant lake water level at the lake shoreline resulting from the seasonal variations of lake water storage. To accommodate these characteristics, the model emphasizes the simulation of groundwater depth's effects on soil water storage and subsequent surface runoff generation, river stage (water level elevation with the river) variation and its effects on groundwater-river water exchange, implementation of lake water variation in the model. The main objectives of this paper are to present the mathematical formulations describing the above processes in modelling lake watersheds in an integrated manner, and to demonstrate the model's suitability for field case studies.

2. Processes and Mathematical Formulations

2.1. Groundwater-Soil Water-Surface Runoff Relations

Surface runoff generation is based on the saturation excess mechanism, which is suitable for wet and humid areas. The model first calculates the maximum soil water storage, S_{max}. Any excess ground rainfall (atmospheric rainfall minus canopy storage) then becomes surface runoff. The maximum soil water storage is expressed as:

$$S_{\max} = h_s \cdot \phi \tag{1}$$

where h_s is the effective thickness of the soil layer (mm); ϕ is the porosity of the soil (-);

The effective soil layer is defined as the layer where active soil water flow occurs, i.e. dynamics of soil water storage, soil water vertical and lateral flows. In areas where the groundwater table is deep enough so that the variations of groundwater table will not affect the soil water storage, the effective soil thickness is determined as the surficial soil layers that most physical parameters can be measured or found in soil database. In areas where the groundwater table is very shallow, the variations of the water table will affect the thickness of unsaturated soil layer, and must be considered in calculating the maximum soil water storage. In this case, the h_s is calculated as the elevation of the grid cell minus the corresponding groundwater head and is expressed as:

$$h_s = Z - h \tag{2}$$

where, Z is the ground surface elevation of the cell (m), h is the groundwater head at the cell (m).

The groundwater head can be obtained from the groundwater flow model of MODFLOW-2005 [5], which solves the following equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S\frac{\partial h}{\partial t} \tag{3}$$

where, K_{xx}, K_{yy}, K_{zz} are values of hydraulic conductivity along the x, y and z coordinates, which are assumed to be parallel to the major axes of hydraulic conductivity; h is the groundwater head; W is a volumetric flux per unit volume representing sources/sinks of water; S is the specific storage of the porous medium; t is time.

For each time step, the model calculates the groundwater head, and through Eq. 2, the groundwater head change is fed to the calculation of maximum soil water storage of Eq. 1 and finally affects the volume of surface runoff generated.

Soil water percolates as groundwater recharge when reaches the water table. Groundwater recharge rate is assumed to be proportional to soil water content. Time lag of the arrival of recharge to groundwater table is considered, similar to that in SWAT [6] and is calculated as:

$$R_G = W_d \cdot [1-\exp(\frac{-\Delta t\cdot\beta_1}{T_{rch}})] \tag{4}$$

where, W_d is the drainable water volume in soil (mm), and is calculated as $W_d = W_s\cdot(1-\phi_{fc}/\phi)$ (W_s is the water storage in soil layer (mm), ϕ_{fc} is the field capacity of the soil); β_1 is an empirical coefficient (-); T_{rch} is the percolation travel time (d), and is expressed as $T_{rch} = D_{wt}/K_{sv}$ (D_{wt} is the depth of groundwater table (m), K_{sv} is the vertical saturated hydraulic conductivity of the soil layer (m/d)); Δt is time step (d).

2.2. River-Groundwater Interactions

Groundwater is in frequent contacts with rivers. Water exchange between aquifers and rivers is an important flow component in watershed hydrological processes. Understanding the interactions of aquifers and rivers is essential in quantifying detailed water balance of lake watersheds, and is also very helpful in exploring pollutants migration paths between surface and subsurface flow domains. Water exchange between groundwater and river depends on several factors, of which the difference of river stage and groundwater head is important. The water exchange rate is usually treated as a linear function of this water level difference, e.g. the RIV package in MODFLOW [5]. In WATLAC, this fundamental function is also adopted to calculate the water exchange rate, but with further improvements regarding the treatment of the river stage. In the original RIV package, the river stage is specified as a computing condition, i.e. the change of the river stage is pre-specified as a computing condition and must be input into the model and remain unaffected by the water exchange between river and groundwater during simulations. This is not very right since water leakage from the river or water discharge to the river will contribute to the change of water balance of the river and consequently affects the change of the river stage, and should be updated for each time step in a simulation. In WATLAC, for each time step the water depth in river is calculated based on the river flow rate, and then the river stage is obtained by considering the river bed elevation. This updated river stage is then passed to the RIV package of MDFLOW to calculate the water exchange rate. The water depth is calculated as:

$$D_r = \sqrt{\frac{A_w}{\gamma} + (\frac{W_2}{2 \cdot \gamma})^2} - \frac{W_2}{2 \cdot \gamma} \tag{5}$$

$$A_w = \frac{Q_r}{V_r} \tag{6}$$

$$V_r = \frac{0.489 \cdot Q_r^{0.25} \cdot i^{0.375}}{n^{0.75}} \tag{7}$$

where, A_w is the wet area of river (m^2); W_2 is the width of river bed (m); γ is the slope ratio of river bank (-); Q_r is flow rate (m^3/d); V_r is the flow velocity (m/d); i is the river bed gradient (-); n is the roughness of river bed (-).

The river stage, h_r is then calculated as:

$$h_r = E + D_r \tag{8}$$

where, E is the river elevation (m).

Water exchange rate between river and groundwater can be calculated as:

$$q_{rg} = C_r \cdot (h_r - h) \tag{9}$$

where, q_{rg} is the rate (m^3/d); C_r is the hydraulic conductance of the river bed (m^2/d);

2.3. Watershed-Lake Hydrological Connections

The water level of lake fluctuates seasonally due to the change of water balance in the lake. The fluctuation of the lake water level may affect the groundwater levels in the areas adjacent to the lake, and further affects the soil water and surface runoff generation. For a fully coupled model, the fluctuations of the lake water level must be coupled in the lake watershed hydrological simulation. To do so, a lake water balance model can be used to update the water storage and the corresponding water level of the lake for each time step. The updated lake water level is then fed to the watershed hydrological model as a boundary condition for groundwater simulation. In WATLAC, a type of lake-land junction cell is introduced to accommodate the simulation of the time-variant lake water level. For the lake-land junction cell, a time-variant water level condition is applied. The water balance of a lake is usually calculated as:

$$\Delta S_{LK} = P_{LK} + q_{LK}{}^i - e_{LK} - w_{LK} - q_{LK}{}^o - q_{LK}{}^g \tag{10}$$

where, ΔS_{LK} is the change of the water storage (m^3); P_{LK} is the lake direct precipitation (m^3); e_{LK} is the lake open water evaporation (m^3); w_{LK} is the water withdrawn from lake (m^3); $q_{LK}{}^i$ is the surface runoff discharged to lake (m^3); $q_{LK}{}^o$ is the surface runoff discharged from the lake (m^3); $q_{LK}{}^g$ is the water exchange between the lake and the groundwater (m^3), and can be calculated as $q_{LK}^{\circ} = C_{LK} \cdot (h_{LK} - h)$ (C_{LK} is the hydraulic conductance of the lake sediment (m^2/d); h_{LK} is the lake water level (m); h is the groundwater head at the lake aquifer (m)).

For most cases, the lake water level can be treated as completely horizontal. If the hydrodynamics of the lake is apparent and must be taken into account, then a more complicated hydrodynamic model is recommended for the lake instead of a simple water balance model for water level calculation.

3. Examples of Model Applications

The model has been applied to several case studies to test and demonstrate its capabilities. For surface and groundwater interaction modelling, the Xitiaoxi catchment of Taihu watershed was used as a test case. The model successfully simulated the stream discharge with a satisfactory accuracy of 0.80, 0.75 and 5% for efficiency coefficient, correlation coefficient and percentage error for daily surface runoff simulation, and an even higher efficiency of 0.92 for monthly simulation. The model also well captured the groundwater dynamics with an absolute error of 0.144 m for head, and the water exchange between the groundwater and the river [7]. The model was also applied to Fuxianhu watershed to quantify its water balance. In that case study, the lake surface area is relative large and lake-land junction cells were used to simulate the linkage of the watershed and the lake. The model application gave important water balance components, such as the overland water flow and groundwater discharge to the lake, which are difficult to observe in-situ [8].

An early application of the WATLAC model to the Poyang lake watershed [9] with a more recent model refinement [10] further demonstrated its suitability to hydrological processes simulation for complicated and large scale watersheds. The model simulated the whole watershed including the five major river catchments with a discretisation of 4km grid cell size as shown in Fig. 1. The observed discharges at the downstream of the rivers were used for model accuracy and efficiency assessment. Model calibration demonstrated a high accuracy, with a Nash-Sutcliffe efficiency of 0.70-0.86 for the calibration period of 1993-1997, and 0.68-0.85 for the validation period of 1998-2002 [10]. Visual comparisons of modelled and observed river discharges for 2001 at selected gauging stations for Ganjiang, Xinjiang and Fuhe are also presented in Fig. 1.

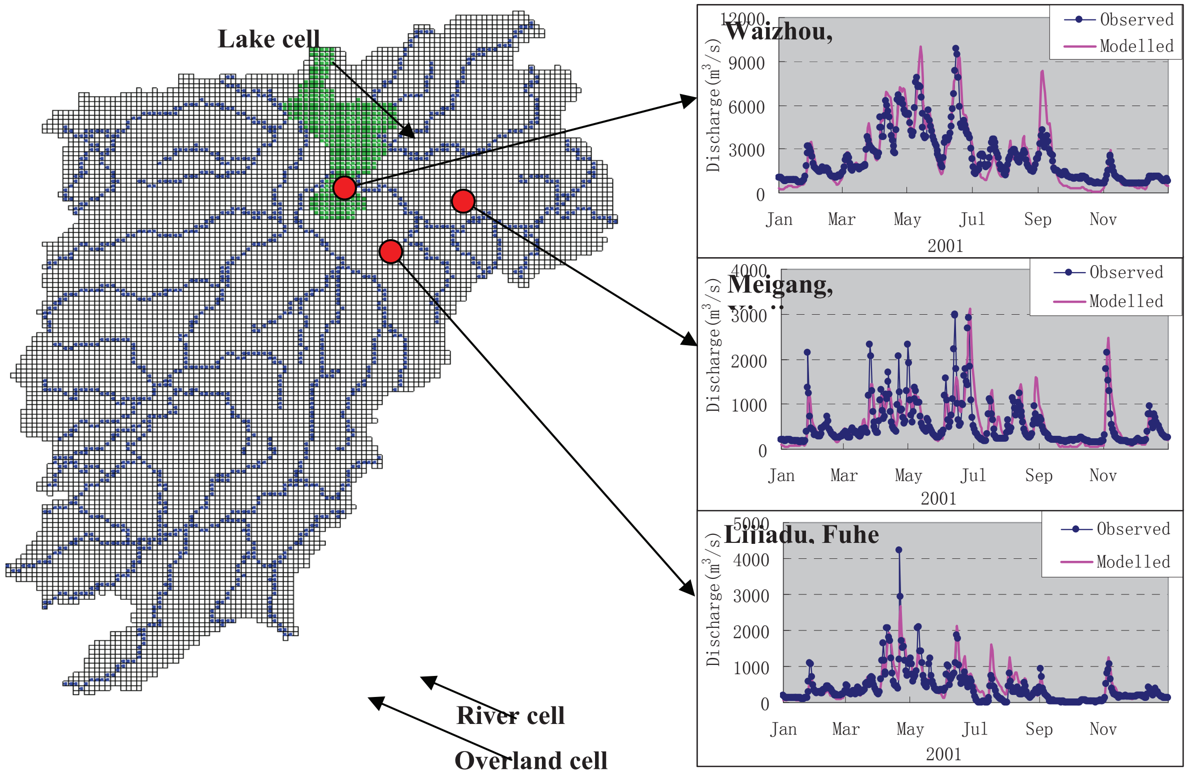

Figure 1 Model grid discretisation for Poyang lake watershed and comparisons of modelled and observed river discharges for 2001 at selected hydrological gauging stations for different rivers.

4. Summary and Conclusions

This paper presents a mathematical model for the integrated hydrological process simulation of lake watersheds. Relation of groundwater-soil water storage-surface runoff generation, river and groundwater interactions and lake-watershed hydrological connection are described in detail. These processes and their corresponding mathematical formulations form the most important science in the model. In addition, these capabilities distinguish this model from other hydrological models readily available in literature. Several field case studies demonstrated that the model is capable of simulating surface and subsurface water flows and their interactions for lake watersheds. The model can be used as an efficient tool to quantify water balance for the watershed and the lake itself. Since the surface water flow is fully coupled with the subsurface water flow, the model can also be used to investigate the impacts of the change of one flow regime on the other. The model is still under development. Further improvements may include the incorporation of a hydrodynamic model for the simulation of lake hydrodynamic process. Capability of simulating effects of reservoir operation on river flow processes is also essential to improve. Moreover, interactions between soil hydrological processes and vegetation growth are important to consider for lake wetlands and form a further model development.

Acknowledgements

This work is jointly supported by Knowledge Innovation Program of Chinese Academy of Science (KZCX2-YW-Q10-3 and KZCX2-YW-337), National Natural Science Foundation of China (40871026) and Science Foundation of Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (NIGLAS2010XK02).

References

[1] HydroGeoLogic: MODHMS, a comprehensive MODFLOW-based hydrologic modeling system, version 3.0. HydroGeoLogic, Herndon (1996).

[2] S.L. Markstrom, R.G. Niswonger, R.S. Regan, D.E. Prudic and P.M. Barlow: GSFLOW - coupled ground-water and surface-water FLOW model based on the integration of the precipitation runoff modeling system (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005), U.S. Geological Survey Techniques and Methods 6-D1, 240 p. (2008).

[3] M.B. Abbott, J.C. Bathurst, J.A. Cunge, P.E. O'Connell and J. Rasmussen: An introduction to the European hydrological system—systeme hydrologique europeen, "SHE", 2: Structure of a physically-based, distributed modelling system. Journal of Hydrology, 87(1–2):61–77. (1986).

[4] Q. Zhang: Coupled simulation of surface and subsurface runoffs for lake catchments. Progress in Geography, 26(5), 1-10. (2007) (in Chinese)

[5] A.W. Harbaugh: MODFLOW-2005, the U.S. geological survey modular ground-water model - the ground-water flow process. U.S. Geological Survey Techniques and Methods 6-A16. (2005).

[6] S.L. Neitsch, J.G.. Arnold, J.R. Kiniry, J.R. Williams and K.W. King: Soil and water assessment tool: Theoretical Documentation, version 2000. Texas Water Resources Institute: College station, Texas; 6–12. (2002).

[7] Q. Zhang and L.J. Li: Development and application of an integrated surface runoff and groundwater flow model for a catchment of Lake Taihu watershed, China. Quaternary International,208(1-2):102-108. (2009).

[8] Q. Zhang and A. Werner: Integrated surface-subsurface modeling of Fuxianhu Lake catchment, Southwest China. Water Resources management,23:2189–2204. (2009).

[9] J. Liu, Q. Zhang, H.J. Zuo, X.L. Jin, L.J. Li and X.C. Ye: A surface runoff model for Lake Poyang watershed. Journal of Lake Sciences, 21(4): 570-578. (2009). (in Chinese)

[10] X.C. Ye, Q. Zhang, B. Li and Q. Hu: A modeling study of catchment discharge to Poyang Lake under future climate in China. Quaternary International, doi:10.1016/j.quaint.2010.07.004. (2010).